Preprint
UCRL-JC-136871

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M. Wedowski, J.H. Underwood, E.M. Gullikson, S. Bajt, J.A. Folta, P.A. Kearney, C. Montcalm, E. Spiller

This article was submitted to
Society of Photo-Optical Instrumentation Engineers 25th Annual International Symposium on Microlithography, Santa Clara, CA, February 27 – March 3, 2000

U.S. Department of Energy

Lawrence Livermore National Laboratory

December 29, 1999

High-Precision Reflectometry of Multilayer Coatings for Extreme Ultraviolet Lithography

Marco Wedowski,[a,1] James H. Underwood,[b] Eric M. Gullikson,[b]
Sasa Bajt,[a] James A. Folta,[a] Patrick A. Kearney,[a] Claude Montcalm,[a] Eberhard Spiller[a]

[a]Lawrence Livermore National Laboratory, Information Science & Technology, Livermore, CA 94550

[b]Lawrence Berkeley National Laboratory, Center for X-Ray Optics, Berkeley, CA 94720

ABSTRACT

Synchrotron-based reflectometry is an important technique for the precise determination of optical properties of reflective multilayer coatings for Extreme Ultraviolet Lithography (EUVL). Multilayer coatings enable normal incidence reflectances of more than 65% in the wavelength range between 11 and 15 nm. In order to achieve high resolution and throughput of EUVL systems, stringent requirements not only apply to their mechanical and optical layout, but also apply to the optical properties of the multilayer coatings. Therefore, multilayer deposition on near-normal incidence optical surfaces of projection optics, condenser optics and reflective masks requires suitable high-precision metrology. Most important, due to their small bandpass on the order of only 0.5 nm, all reflective multilayer coatings in EUVL systems must be wavelength-matched to within ±0.05 nm. In some cases, a gradient of the coating thickness is necessary for wavelength matching at variable average angle of incidence in different locations on the optical surfaces. Furthermore, in order to preserve the geometrical figure of the optical substrates, reflective multilayer coatings need to be uniform to within 0.01 nm in their center wavelength. This requirement can only be fulfilled with suitable metrology, which provides a precision of a fraction of this value. In addition, for the detailed understanding and the further development of reflective multilayer coatings a precision in the determination of peak reflectances is desirable on the order of 0.1%. Substrates up to 200 mm in diameter and 15 kg in mass need to be accommodated. Above requirements are fulfilled at beamline 6.3.2 of the Advanced Light Source (ALS) in Berkeley. This beamline proved to be precise within 0.2% (rms) for reflectance and 0.002 nm (rms) for wavelength.

Keywords: Extreme ultraviolet lithography, synchrotron radiation, reflectometry, reflective multilayer coatings, uniformity

1. INTRODUCTION

For more than three decades, using shorter wavelengths and resolution enhancement techniques, optical lithography has enabled the semiconductor industry to deliver integrated circuits with ever increasing device density. It is anticipated that the introduction of excimer lasers in the deep ultraviolet spectral range will continue this trend to feature sizes below 100 nm. For further reduction of critical dimensions down to 25 nm, Extreme Ultraviolet Lithography (EUVL) is a promising technology. Currently efforts are underway in Japan, Europe and the United States in order to develop the necessary components such as light sources, condenser systems, projection optics, and masks. Synchrotron radiation sources are important in these efforts not only as a potential radiation source for lithographic printing, but also as a radiation source for the necessary metrology instruments. The Center for X-Ray Optics (CXRO) at the Advanced Light Source (ALS) in Berkeley as well as the Physikalisch-Technische Bundesanstalt (PTB) at the electron storage ring facility for synchrotron radiation BESSY in Berlin have installed several dedicated beamlines in order to serve the needs for the development of EUVL. Applications include the calibration of detectors, interferometry, scatterometry and reflectometry. Of particular importance for precision manufacturing of multilayer coated EUVL components are the two reflectometers[1,2,3], which are installed at CXRO and PTB. Although the deposition of reflective multilayer coatings is a deterministic process, it requires continuous feedback on the result of individual coating runs. Most important is the feedback on the multilayer thickness uniformity in addition to the verification of high peak reflectance. Based on the data obtained, magnetron sputter deposition is a robust method, which results in fast convergence of the coating prescription development process. For fast convergence of the process the reflectometers must not only meet stringent optical and mechanical requirements, but also must enable short turn-around times and provide highly reliable data.

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[1] Present address: Carl Zeiss, 73446 Oberkochen, Germany

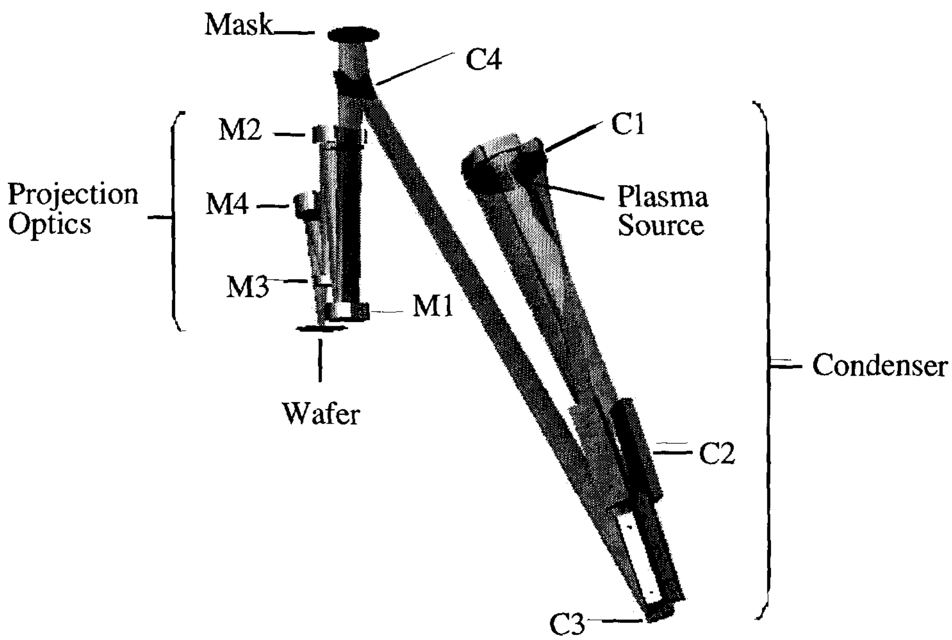
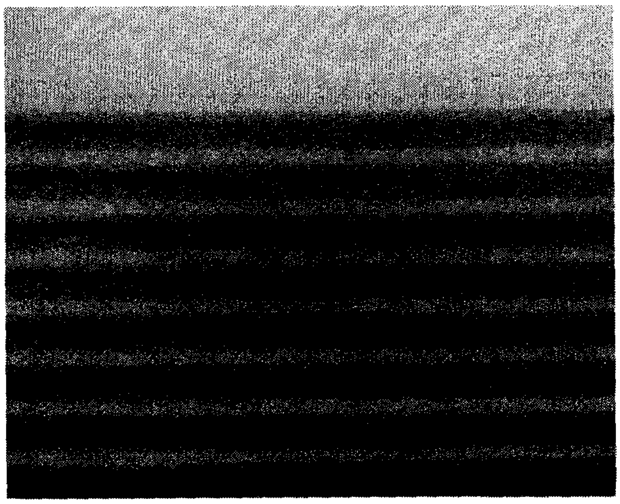


Figure 1. Layout of the ETS showing the EUV optical path from the laser-produced plasma source volume to the wafer stage through condenser optics, reticle stage, and projection optics.

2. REFLECTIVE COATINGS FOR THE ENGINEERING TEST STAND

Figure 1 shows the optical layout of the Engineering Test Stand[4] (ETS), which is currently being built by the Virtual National Laboratory (VNL). All of the optical elements in the ETS are illuminated near normal incidence with the exception of the grazing incidence C2 mirror assembly and the C4 mirror. These grazing incidence mirrors are coated only with a single layer of ruthenium and provide broadband reflectance of 91% (at 8°) for C2 and 80% (at 16°) for C4. These values are achieved by a single reflection at the ruthenium-vacuum interface. In contrast, the normal-incidence elements, including the patterned mask in the reticle stage, achieve high reflectance by several reflections in a periodic molybdenum-silicon (Mo/Si) multilayer stack exploiting interference effects. Due to the resulting narrow optical bandpass the multilayer coatings require a precisely wavelength-matched bilayer thickness. For Mo/Si multilayers a typical FWHM bandwidth is 0.55 nm. In this case a wavelength matching of all components within ±0.04 nm is sufficient in order to achieve 96% of the ideal throughput. For overall high optical throughput it is also desirable to have peak reflectances of more than 65% near normal incidence. Since the condenser elements C1 and C3 are illuminated at different average angles in different locations, graded thickness multilayer coatings are required in order to maintain constant FWHM center wavelength for variable illumination angles.

For high-resolution lithographic printing multilayer coatings on EUVL projection optics must preserve the 0.25 nm (rms) figure of the mirror substrates. Considering the overall thickness of a multilayer coating of 300 nm, this means that the allowable relative error added is less than 0.1%. Specifications are tight because purely geometrical distortion of the wavefront due to surface deformation is even enhanced by interference effects inside a non-uniform multilayer. On the other hand, multilayer non-uniformites typically have low spatial frequencies. Furthermore, tilting and focussing during final alignment of the optical system can compensate for first and second order polynomial components of the non-uniformities. Therefore, the practical criterion for multilayer bilayer thickness uniformity is an allowable tolerance of ±0.1% peak-to-valley. As a consequence the absolute bilayer uniformity tolerance for wavelength near 13 nm is on the order of 0.01 nm peak-to-valley, which requires a measurement precision on the order of 0.002 nm.



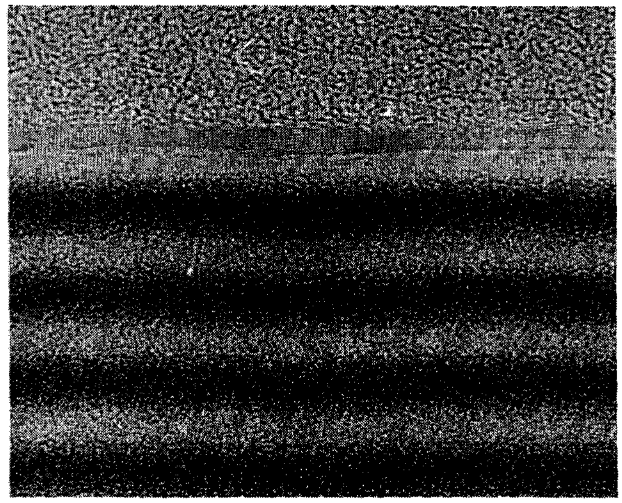


Figure 2. TEM cross sectional micrographs near the surface of Mo/Si (left) and MoRu/Be (right) multilayer coatings. A typical bilayer thickness is 6.9 nm (Mo: 2.8 nm/Si: 4.1 nm) for Mo/Si and 5.8 nm (MoRu: 2.4 nm/Be: 3.4 nm) for MoRu/Be.

TEM micrographs of the most promising multilayer material combinations Molybdenum/Silicon (Mo/Si) and Molybdenum-Ruthenium/Beryllium (MoRu/Be) for reflective multilayer coatings in the EUV spectral range are shown in Figure 2. The multilayer stacks consist of up to 50 bilayers of absorber-spacer material combinations and have a total thickness of about 300 nm. The top surface of standard Mo/Si multilayer coatings is terminated with a 1.3-nm native SiO_2 layer, while standard MoRu/Be multilayers are terminated with a native 3.5-nm BeO layer. A typical wavelength for Mo/Si multilayers is 13.4 nm. MoRu/Be multilayers can be used at wavelengths as short as 11.4 nm, which is a wavelength well-suited for use with a laser plasma Xe cluster source. Both multilayer systems have peak reflectances higher than 65% and have proven to be stable over a long period of time. The remaining challenge consisted in the deposition of highly uniform films over large, figured optical substrates. A complete set of Mo/Si multilayer-coated components for the ETS meeting uniformity and reflectance specifications has been fabricated.

3. BEAMLINE AND REFLECTOMETER

3.1 Overview of ALS Beamline 6.3.2

The Center for X-ray Optics (CXRO) has built and is operating beamline 6.3.2 of the Advanced Light Source (ALS) in Berkeley[1]. Beamline and reflectometer were especially designed for the characterization of multilayer coated EUVL optics. The main features of the beam delivered are spectral purity, small beam diameter, and high stability. The reflectometer features a detector arm with several detectors, including photodiodes, a channeltron and a CCD camera. Samples ranging from small test pieces to final ETS optics can be easily accommodated and manipulated with highly precise rotational and translational motions. Short pump-down times are achieved by a differentially pumped section, which separates the ultra-high vacuum of the monochromator from the vacuum conditions in the reflectometer. The interior of the reflectometer is easily accessible through an air-purged area by opening a large door on the side of the reflectometer tank. Overall the beamline provides unique features, which combine high precision with the flexibility to perform experiments in a variety of disciplines such as atomic physics and materials science.

3.2 Optical Layout

Synchrotron radiation emitted from the source volume is collected by the beamline through a 4-jaw aperture, which clips the beam in a way that only the central portion of the horizontal focussing mirror is illuminated. This mirror forms a horizontal image of the bending magnet source with 1:1 magnification in the center of the reflectometer. The spherical converging mirror illuminates the exit slit with a vertical image of the source demagnified by a factor of 10. This magnification is slightly modified by the factor $\cos(\alpha)/\cos(\beta)$ with α and β being the angles enclosed by the beam and the grating. The bendable and adjustable vertical focusing mirror images the exit slit with magnification 1:1 focussed near the center of the reflectometer. This optical design results in a spot in the reflectometer chamber, which is horizontally an unmagnified image of the bending magnet source. Vertically the spot in the reflectometer is an unmagnified image of the exit slit (see Figure 3).

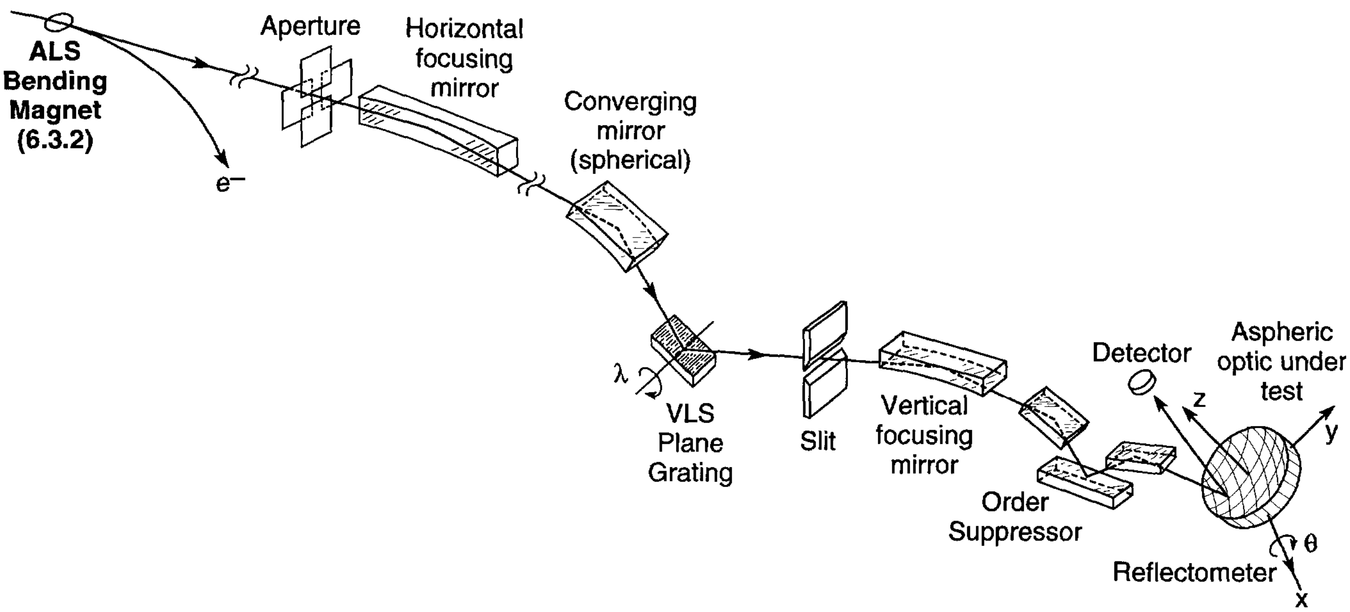


Figure 3. Schematic view of beamline 6.3.2 of the Advanced Light Source (ALS) in Berkeley. The vertical focusing mirror is bendable in order to adjust the focus location. Filter wheels are located between the exit slit and the vertical focussing mirror.

3.3 Monochromator

A plane varied-line spacing (VLS) grating operating in the converging light produced by the concave spherical converging mirror represent the core elements of the beamline[5]. Together with the exit slit they form the monochromator. The proper choice of line-spacing variation on the grating facilitates the correction of spherical aberrations introduced by the high demagnification of the converging mirror. As a major advantage of this configuration, the wavelength can be tuned by a simple rotation of the grating about its center. There are no other moving parts such as translating mirrors or exit slits. The mechanical simplicity of the design results in high flux, accurate knowledge of the wavelength, and reliability of the wavelength calibration. In routine operation the wavelength calibration is derived with sufficiently high precision from the direction of the zero-order specular reflection from the grating. Only occasionally the wavelength calibration is directly compared to the position of atomic absorption lines using a permanently mounted gas cell. Because of the excellent source stability, which is consistently achieved at the ALS, slitless operation of the monochromator carries no penalty of drifts in the wavelength calibration between refills of the storage ring. However, for high-precision measurements the energy calibration is routinely checked after each refill.

3.4 Filter Wheel and Higher Order Suppressor

Two filter wheels are installed in the beamline between the exit slit and the vertical focussing mirror. These carry silicon and beryllium foils whose L-edges are located in the EUV spectral range (Si: near 12.4 nm, Be: near 11.1 nm). They are used to improve the spectral purity of the beam. The filter wheels also carry other filter materials and phosphors for beam visualization and attenuation. For greater spectral purity than can be obtained with filters alone, a 3-mirror order suppressor can be inserted into the beam between the vertical focussing mirror and the reflectometer chamber. The center mirror operates at twice the glancing angle of the two outer mirrors in a way that the beam is neither deviated nor translated when the beam passes through the order sorter. In practice this feature can be used to verify proper alignment of the beam.

3.5 Reflectometer

The reflectometer consists of two Huber goniometers mounted on a vacuum vessel. One axis carries the sample, for example a aspheric multilayer coated mirror, in the center of the reflectometer vacuum tank. The other axis carries the detectors on a rotating arm. Through-vacuum linear motions translate the sample in three orthogonal directions with a precision of 0.1mm. Samples can be mounted on customized fixtures, including two dedicated rotational stages for full field 150 mm and 200 mm wafer and ETS optics characterization. The heaviest ETS optics in its coating fixture together with the rotational stage weighs nearly 20 kg, which is the maximum weight handled so far in the reflectometer. The azimuthal orientation of the sample on the rotational stages can be freely adjusted while tip and tilt adjustments can made with a precision of 0.01° at any reflection angle desired. The maximum effective sag allowable for a sample to be measured without breaking the vacuum is 20 mm. The valve at the front of the reflectometer has a glass window. When closed the sample can be positioned and aligned using visible synchrotron light, with the reflectometer at atmospheric pressure or under vacuum. An external CCD camera and a TV monitor facilitate precise positioning of the samples. A scroll pump and a vibration isolated cryo pump with 4000 l/s pumping speed, which is especially efficient for water vapor, are used in order to reach a typical pressure of 10^{-7} Torr for reflectometry. Together with protocols, which minimize the exposure of the reflectometer chamber walls to air moisture, pump down times of less than 20 minutes are routinely achieved.

3.6 Measurement Procedures

After proper alignment of the sample the basic properties measured at any given location on a multilayer-coated surface are peak reflectance, FWHM center position of the peak and the FWHM bandwidth of the peak. This information can be extracted from reflectance curves, in which the reflectance of a multilayer mirror is measured as a function of the wavelength of the incident beam in the vicinity of the first-order Bragg peak. For proper alignment of the sample the following steps are required before any measurements are made. 1. Pointing the beam perpendicular through the reflectometer axis. 2. Defining the forward direction with the detector (2θ calibration). 3. Positioning of the sample surface on the reflectometer axis (z adjustment). 4. Defining the measurement location (x and y adjustments). 5. Adjusting the tip and tilt of the sample at the measurement angle. 6. Focussing of the beam in order to compensate for beam divergence caused by the curvature of the sample. Without careful execution of this checklist peak reflectances and FWHM center positions measured would be affected by systematic errors. Peak positions measured are sensitive to geometrical errors due to their dependence on the exact angle of incidence. Peak reflectances measured are sensitive to spatial conversion efficiency variations on the detector. Therefore it is desirable to hit nearly identical areas of the photodiode with the direct and the reflected beam, whose intensity ratio represents the reflectance.

3.7 Data Acquisition and Analysis

Data collection and beamline control are facilitated by a UNIX workstation through the graphical user interface (GUI) of a LabView program. The software allows to control the settings of a number of movements within the beamline and the reflectometer. Automatic scans of the different axes can be programmed. This is the mode used to acquire reflectance curves at any given location on a multilayer coating. At each setting during such an automatic scan the reading of the axis scanned, the detector current, the reference mirror current and the storage ring current are stored in ASCII format. Furthermore two-dimensional scans can be programmed, which combine the movements of two independent axes in a systematic raster. This mode is used to determine the reflectance of a multilayer coating at a given wavelength across the surface. It is also used to automatically acquire several reflectance curves along a line across the multilayer-coated surface. All data stored on the UNIX workstation is immediately available via NFS on a beamline PC. Individual reflectance curves can be immediately evaluated using an EXCEL spreadsheet, while 2-dimensional scans are evaluated using IDL procedures. Data obtained is distributed throughout the VNL via FTP.

4. MEASUREMENT PRECISION

4.1 Overview

High-precision measurements of the reflective properties of multilayer coatings in the EUV spectral range require full control over the experimental geometry, spectral purity of the radiation source and suitable detectors. Synchrotron radiation facilities are ideally suited for precision reflectometry because they provide a well-collimated beam, high intensity, wide spectral range, and a clean environment. Beamline 6.3.2 at the ALS in Berkeley[1] and the PTB SX 700 beamline at BESSY in Berlin[2,3] utilize synchrotron-based reflectometers with the same level of precision. Other facilities utilizing laser produced plasma reflectometer also provide reflectivity data, but their precision may be limited by higher order contamination of the radiation and by statistical noise introduced by a relatively low flux level. Until a few years ago there was a significant uncertainty about the reliability of reflectometry data. However, today with at least two synchrotron-based reflectometers delivering essentially identical results this uncertainty appears to be fully resolved.

4.2 Definitions

The following definitions are routinely used for the evaluation of data obtained at ALS beamline 6.3.2. *Peak reflectance* is currently defined as the highest discrete reflectance value obtained along a reflectance curve (see Figure 4) in the vicinity of the main Bragg peak. This definition has the advantage of simple numerical realization, but its precision is strongly limited by statistical variations in the experimental data and the step width used. Other concepts including fits to model the shape of experimental reflectance curves may improve the situation. *FWHM center wavelength* is defined as the average of the two wavelengths, at which a linear fit between two consecutive points of the reflectance curve crosses the half value of the peak reflectance. The repeatability of results of measurements using this method is very high because the slope of multilayer reflectance curves is highest near the half value of the peak reflectance. Evaluation of sequentially measured reflectance curves shows statistical variations only on the order of 0.0001 nm when the FWHM center wavelengths are compared. This definition does not depend on the location of the absolute reflectance maximum, which for a typical Mo/Si coating consistently appears about 0.03 nm higher than the FWHM center wavelength. Application of the above definition allows sub-resolution precision in a way that measurement tolerances are much smaller than the bandwidth of the multilayer under investigation as well as much smaller than the spectral bandwidth of the beam to probe the multilayer. For this reason there remains an uncertainty about the exact spectral profiles of the multilayer reflected beam and the probing beam. However, a concrete manifestation of such effects has not yet been identified. *FWHM bandwidth* is defined as the difference of the two wavelengths used in the definition of the FWHM center wavelength.

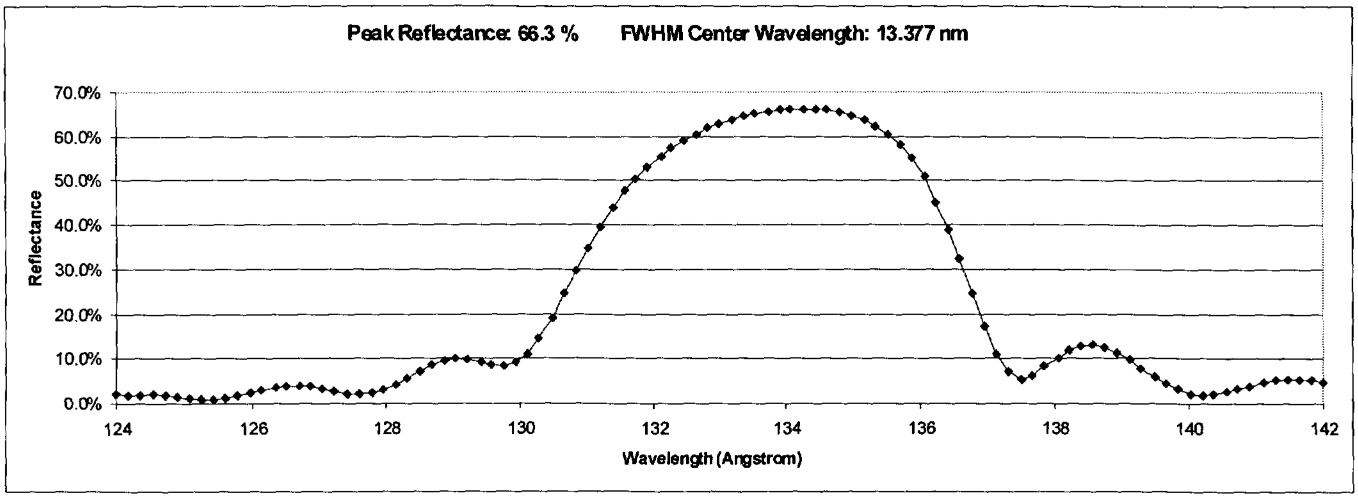


Figure 4. Typical Mo/Si multilayer reflectance curve obtained at ALS beamline 6.3.2 as ratio of photodiode currents obtained in wavelength scans for the direct beam and the multilayer reflected beam.

4.3 Atomic Level Precision

Atomic level measurement precision of multilayer thickness becomes possible due to the resonant nature of the multilayer reflection process, which causes sharp, distinctive features in reflectance curves. These features directly relate to the optical properties and thickness of the multilayer coating. Although individual layer properties remain experimentally inaccessible, the normalized multilayer stack thickness is related to the FWHM center wavelength, which can be measured consistently with sub-Angstrom precision of 0.002 nm. This is just the precision, which can be achieved at ALS beamline 6.3.2 in atomic physics and solid state physics experiments. An important assumption for the utilization of the above mentioned precision is that for high reflectance multilayer coatings the peak reflectances, the bandwidth and the shape of reflectance curves are nearly identical.

4.4 Beamline Wavelength Calibration

ALS beamline 6.3.2 and the PTB SX700 beamline derive their calibration from first principles, independently. ALS beamline 6.3.2 has a well-known simple geometry, which directly correlates the grating angle with a wavelength via a linear relation. The two coefficients, which describe this linear relation, are experimentally derived from the literature value of 13.595(10) nm for the Krypton Kr $3d_{5/2}$ - 5p atomic resonance[6]. The PTB SX700 monochromator has a more complex geometry and therefore requires a more complex calibration scheme. First, the monochromator must be aligned in a way that for different C-factors[7] identical wavelength values are obtained. Once this condition is fulfilled photon energies obtained must be corrected according to the relation $E'=E- \Delta E_{Cu} (E/E_{Cu})^{3/2}$ with E_{Cu} being the energetic location of the copper Cu L_{III} absorption edge[8] at 933.1(1) eV and ΔE_{Cu} being the difference to this value observed for the Cu L_{III} edge in a given experimental run. For the conversion from the energy scale to the wavelength scale the factor 1239.842 eV/nm is used.

4.5 Comparison of Center Wavelength Results

First comparison experiments between ALS beamline 6.3.2 and the PTB SX700 beamline were performed in 1996[9,10]. At that time the two beamlines already yielded satisfactory agreement for the peak reflectance and the center wavelength of a single sample. Further experiments were performed in 1998 on five samples, which were measured at several locations. The main goal was to demonstrate that a multilayer gradient as small as 0.002 nm/mm could be reliably detected in both facilities. Results on a standard Mo/Si reflective multilayer coating deposited at LLNL are summarized in Table 1. PTB data is derived from the calibration certificate[12] issued for measurements performed on sample M1980416 A-B. The wavelength gradient on the order of 0.002 nm/mm along the y direction is consistently revealed in measurements at both facilities. Both data sets deviate systematically by only 0.001 nm. Since this value represents the relative uncertainty of the literature values for the Cu L_{III} absorption edge and the Kr $3d_{5/2}$ - 5p atomic resonance, the wavelength results obtained can be described as identical for both beamlines. However, it needs to be pointed out that in order to achieve this precision a large number of parameters needs to be very well controlled. In particular, the two beamlines need to be precisely calibrated, the measurement geometry needs to be fully controlled, and the sample position and orientation need to be precisely determined. Loosing control in one of these areas may already destroy the precision for the FWHM center wavelengths.

Position	x = -1 mm	x = 0	x = 1
y = 1 mm		**PTB:** 13.429 nm	
		ALS: 13.430 nm	
y = 0 mm	**PTB:** 13.427 nm	**PTB:** 13.427 nm	**PTB:** 13.427 nm
	ALS: 13.428 nm	**ALS:** 13.428 nm	**ALS:** 13.427 nm
y = -1mm		**PTB:** 13.425 nm	
		ALS: 13.426 nm	

Table 1. Comparison of FWHM center wavelength profiling results obtained at ALS beamline 6.3.2 and PTB's SX700 on Mo/Si multilayer coated sample M1980416 A-B. This coating was deposited at LLNL on a 25 mm diameter fused silica flat fabricated by General Optics. The measurement angle was 85° at CXRO and 88.5° at PTB. Values shown are calculated according to the formula λ (90°) = λ (measurement angle)/sin (measurement angle).

4.6 Comparison of Peak Reflectance Results

Reflectance values on a number of samples were recently found to be consistently within ±0.2 % when measured at both facilities. However, a newly cleaved piece of reference coating M1960821A2 this time yielded 66.4 % at PTB, while later 66.1 % were obtained at the ALS. This is the opposite of earlier reported 66.1 % for measurements at PTB and 66.5 % for measurements at the ALS[10]. The conclusion is that these samples suffer from surface contamination during repeated handling as a reference sample. Lower values are consistently achieved after repeated use. Already a monolayer of surface contamination may cause a reflectance loss on the order of 0.5 %. An additional complication in the precise determination of absolute reflectances is the fact that scattering can cause reflectance degradation. Scattering is caused by multilayer interface roughness, which is due to the replication of substrate roughness during the multilayer growth process[11]. Depending of the substrate quality and the multilayer deposition geometry scattering can occur with different intensities and angular distributions. Therefore a beam that is reflected from a multilayer coated surface is surrounded by more or less scattered light. As a consequence, depending on the size and geometry of the detectors used, the absolute values obtained in reflectance measurements may be affected. The absolute error made due to this problem is estimated to be on the order of 1% for standard multilayer coatings. However, in practice, identical detector geometries are used for all measurements and therefore reflectances are always measured with a similar angle of acceptance for scattered light. This gives a sufficiently precise distinction between scatter and the reflected beam. Overall under well-controlled conditions results of peak reflectance measurements are repeatable within ±0.2%.

5. APPLICATIONS

5.1 Overview

The reflectometer at ALS beamline 6.3.2 is supporting a variety of different activities within the VNL. The most important application is support for the development of multilayer coating prescriptions for uniform, high reflectance coatings for curved optics and mask blanks. Feedback is provided on the optical properties of multilayer coatings deposited in repeated surrogate runs. Another application is the feedback on reflective properties in the development of new multilayer systems like MoRu/Be. Also the assessment of temporal, thermal, chemical and radiation stability of multilayer reflective coatings is an important application. In all areas it is necessary to maintain high reliability of the data, high throughput, and short turn-around times. During the last two years at ALS beamline 6.3.2 a very large number of samples was measured. This situation has recently been relieved by the commissioning of ALS beamlines 11.3.2 for mask blank defect detection and ALS beamline 6.3.1 for reflectometry.

5.2 Projection Optics Coating

The main goal of the projection optics coating was the deposition of uniform, high reflectance multilayer coatings on all four curved ETS mirror substrates[13]. In order to provide sufficient capabilities to accommodate the size and weight of the ETS mirrors, the coating tool MAG 1 located at the Lawrence Livermore National Laboratory (LLNL) needed to be upgraded. The multilayer deposition process model was developed and the uniformity for multilayer coatings on 150 mm flat wafers was greatly improved to below 0.1 % peak-to-valley according to measurements at ALS beamline 6.3.2. The method to achieve coating uniformity consists in controlling the exposure time of the mirror substrates over the sputter sources by modulation of the substrate velocity. Based on the experience gained during the coating runs on flats, uniformity within 0.1% peak-to-valley could also be achieved on curved substrates after several iterations on surrogates with feedback from ALS beamline 6.3.2. The figure errors added by the multilayer coating along with the normalized film thickness on the different mirrors are shown in Figure 5.

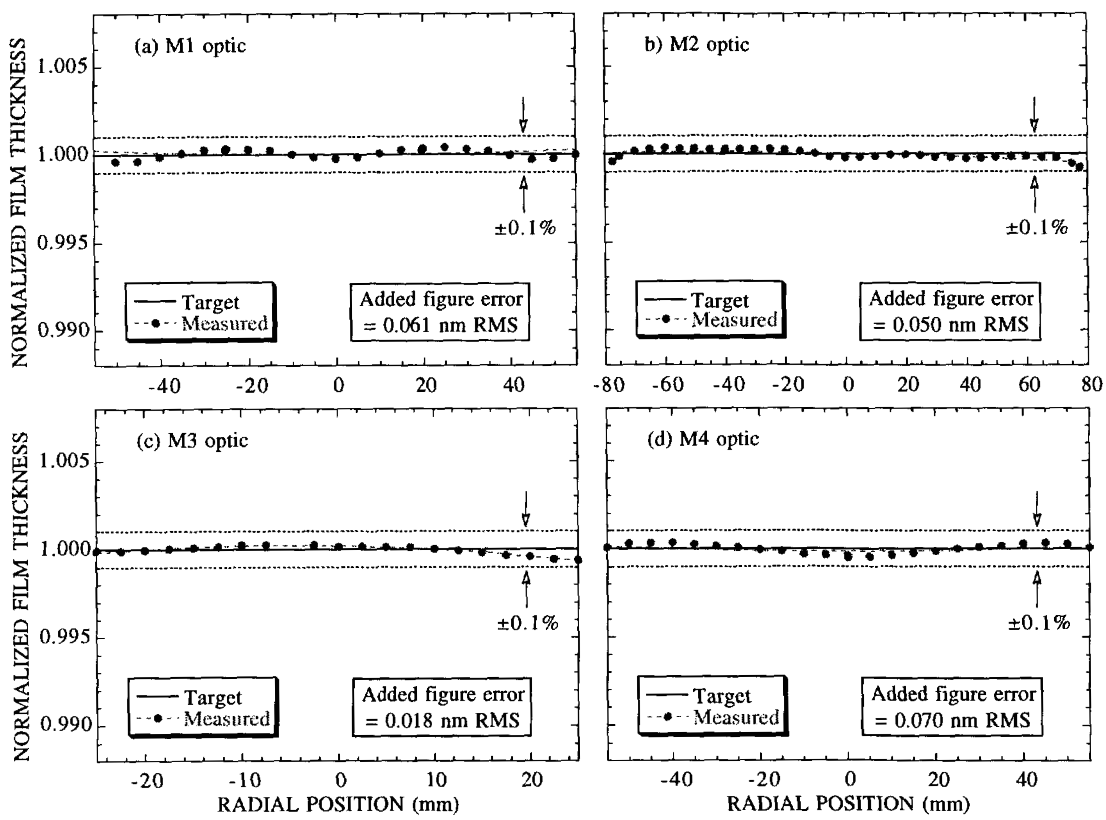


Figure 5. Normalized film thickness of the multilayer coating achieved on the ETS M1, M2, M3, and M4 projection optics. Uniformity within less than 0.1% on all mirrors has been achieved by several iterations involving the coating tool and ALS beamline 6.3.2. The figure error added by the multilayer deposition is negligible for the resolution of the final optical system. This conclusion has been confirmed by at-wavelength interferometry performed with the assembled four-mirror system.

5.3 Condenser Optics Coating

Condenser optics coating represents a different challenge due to the large number of individual pieces to be coated. Compared to the projection optics coating the specifications are relaxed, but instead a precise gradient is required. Due to the large sag and the steep angles encountered on the C1 condenser optics, a higher number of iterations with feedback from ALS beamline 6.3.2 were necessary. In contrast development of the coating prescription on the flat C3 condenser elements required only a few iterations. Results obtained on C1 condenser optics are shown in Figure 6.

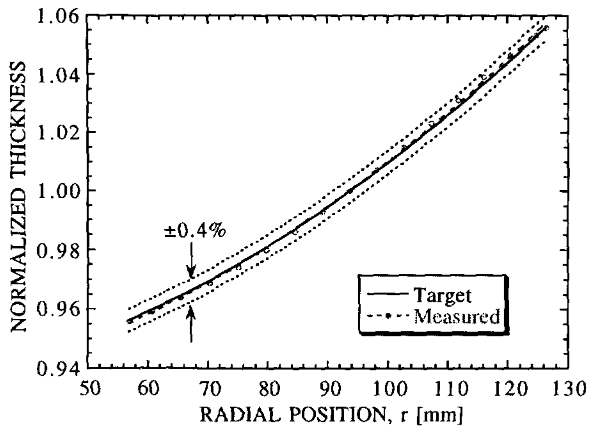


Figure 6. Normalized film thickness of the multilayer coating achieved on the ETS C1 condenser optics. The gradient achieved is sufficiently precise in order to ensure wavelength matching for different radial positions.

5.4 Mask Blank Development

FWHM center wavelengths and radial uniformity profiles of mask blanks[14] coated at LLNL are routinely measured at ALS beamline 6.3.2. Several holders that allow simultaneous pump-down of two 150 mm or 200 mm wafers allow efficient utilization of the beamtime. By continuous feedback it was possible to achieve wavelength matching and uniformity on mask blanks within 0.1 nm. However, currently the conditions, which allow optimim uniformity are not yet compatible with the required low defect density on mask blanks. Uniformity is best for multilayer deposition at an angle, while defect mitigation is best for near normal incidence deposition.

5.5 Patterned Mask Qualification

Before printing patterned masks[15] in the 10x EUVstepper at Sandia National Laboratories, reflectance curves are routinely obtained at ALS beamline 6.3.2 in order to correlate the optical properties of the multilayer to the printing results obtained. Additionally, the development of mask patterning processes requires continuous feedback of possible effects on the multilayer coating. In addition to thermal effects, the influence of chemicals used during the maskpatterning process needs to be assessed.

5.6 Radiation Stability Assessment

Multilayer coatings are exposed to a special environment in an EUVL optical system. In addition to the EUV radiation load the coatings are exposed for a long time to residual gases in the vacuum. Although degradation of the bulk of reflective multilayer coatings could not yet be detected, there is evidence for chemical modification of the multilayer surface under EUVL conditions[15]. Carbon deposition as well as enhanced oxidation of the multilayer surfaces has been observed under EUV illumination in vacuum. Reflectometry at ALS beamline 6.3.2 has been used in order to assess the effects of long term exposure on the optical properties of multilayer coatings. No modification of the FWHM bandwidth or the FWHM wavelength has been observed. The peak reflectance degraded under high vacuum conditions by only 2% after exposure to an EUV dose equivalent to several months of EUVL operation.

5.7 Multilayer Development

Using ALS beamline 6.3.2 extensive efforts have been made in order to assess the stress, reflectance, and temporal stability of sputter-deposited Mo/Si and Mo/Be reflective multilayer coatings[17]. Also the use of capping layers, and techniques for uniform deposition of multilayer coatings have been extensively investigated using the beamline[18]. Development of Mo/Be multilayer coatings, which are better wavelength-matched matched to laser produced Xe plasma sources[19], has recently been replaced by the development of MoRu/Be multilayer coatings. MoRu/Be multilayer coatings show advantages in high reflectance, low stress, and preservation of substrate smoothness during deposition.

6. OUTLOOK

The Mo/Si and Mo/Be magnetron sputtering multilayer deposition systems MAG 1 and MAG 3 installed at LLNL are currently being replaced by a new magnetron sputter system MAG 4 and a new ion beam deposition system. They are located in a clean room area together with the existing low defect-density (LDD) ion beam deposition tool for multilayer coating of mask blanks. Various mask blank inspection tools are located in the area as well. In order to drastically reduce the turn-around time for reflectometry of mask blanks an on-site EUV reflectance monitor is currently being designed. This system will be directly attached to the LDD tool and represents a fixed-angle laser plasma reflectometer. Completion of this device will facilitate tight feedback for the optimization of multilayer ion beam deposition on mask blanks.

ACKNOWLEDGEMENTS

This work was performed under the auspices of the U. S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48. Funding was provided by the Extreme Ultraviolet Limited Liability Company (EUV LLC) under a Cooperative Research and Development Agreement (CRADA).

The work performed at the University of California Lawrence Berkeley National Laboratory is supported through a CRADA with the Extreme Ultraviolet Limited Liability Company (EUV LLC) and by the U.S. Department of Energy under Contract No. DE-AC03-76F00098.

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